RI 7814

Bureau of Mines Report of Investigations/ 1973

Shear Testing of Simulated Lunar Soil in Ultrahigh Vacuum

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 7814

Shear Testing of Simulated Lunar Soil in Ultrahigh Vacuum

By B. V. Johnson, W. W. Roepke, and K. C. Strebig
Twin Cities Mining Research Center, Twin Cities, Minn.

UNITED STATES DEPARTMENT OF THE INTERIOR
Rogers C. B. Morton, Secretary

BUREAU OF MINES
John D. Morgan, Jr., Acting Director

The work upon which this report is based was performed under NASA contract R-09-040-001.

This publication has been cataloged as follows:

Johnson, Bradley V

Shear testing of simulated lunar soil in ultrahigh vacuum, by B. V. Johnson, W. W. Roepke, and K. C. Strebig. [Washington] U.S. Bureau of Mines [1973]

18 p. illus., tables. (U.S. Bureau of Mines. Report of investigations 7814)

Includes bibliography.

Based on work performed under NASA contract R-09-040-001.

1. Shear strength of soils—Testing. 2. Lunar petrology. 3. Lunar geology, I. Roepke, Wallace W., jt. auth. II. Strebig, Kelly C., jt. auth. III. U.S. Bureau of Mines. IV. Title. V. Title: Lunar soil, Simulated. (Series)

TN23.U7 no. 7814 622.06173

U.S. Dept, of the Int. Library

CONTEXTS

ILLUSTRATIONS

TABLES

SHEAR TESTING OF SIMULATED LUNAR SOIL IN ULTRAHIGH VACUUM

by

B. V. Johnson,[1] W. W. Roepke,[2] and K. C. Strebig[3]

ABSTRACT

The Federal Bureau of Mines has conducted research in support of the National Aeronautical and Space Administration's (NASA) Apollo program to acquire fundamental scientific and engineering knowledge of lunar-mineral resources for NASA's Office of Advanced Research and Technology. Equipment and techniques were developed to conduct soil shear tests in a simulated lunar environment. Shear tests performed with this equipment in ultrahigh vacuum and controlled laboratory atmosphere showed that simulated lunar soil increased in strength in the simulated lunar environment.

INTRODUCTION

The Federal Bureau of Mines is engaged in a research program to acquire fundamental scientific and engineering knowledge of lunar-mineral resources for the National Aeronautical and Space Administration's (NASA) Office of Advanced Research and Technology. This program envisions the utilization of lunar soil and rock to support future manned space missions. One part of this investigation is the assessment of the problems associated with the handling and storage of fine particulate materials on the moon.

To assess these materials handling problems, it is necessary to determine certain basic physical properties that would influence the handling and storage of lunar soil in the lunar environment. One of the important physical properties is the shear strength of the soil. Because the tests had to be conducted in an ultrahigh vacuum (UHV) chamber, which requires long pumpdown times, it was necessary to use a torsional shear tester that allowed repetitive tests on single samples of powder material without opening the vacuum chamber between tests.

The preliminary laboratory atmospheric work was performed by D. E. Nicholson at Spokane Mining Research Center (SMRC) and has been

---

[1] Physicist.
[2] Principal vacuum specialist.
[3] Mining engineer.

described elsewhere (5).[4] The simulated lunar environment testing was performed by Twin Cities Mining Research Center because of previous knowledge of lunar materials and its capability in UHV research.

This report describes the equipment and procedures used to determine the shear strength of simulated lunar soil (SLS) and to compare the shear strength of SLS under atmospheric and under UHV conditions.

ACKNOWLEDGMENT

M. J. J. Gangler of NASA's Office of Advanced Research and Technology, Washington, D.C., monitored the work upon which this report is based.

SIMULATED LUNAR SOIL

Since the exact state of rocks and soils on the lunar surface was not known, it was necessary to make some assumptions. If the worst case for shearing forces of soil in a lunar environment is assumed, one must be prepared for the possibility that hundreds of millions of years of exposure to hard vacuum, radiation, and micrometeorite bombardment in space may have produced a lunar surface that is totally outgassed to a considerable depth. Soil and rock surfaces outgassed to such an extent approach an atomically clean condition where the rock/vacuum interface would have less than one-half monolayer of any molecules superimposed upon the rock surface.

Despite the presence of a very low residual gas pressure in the UHV system simulating the lunar atmosphere, it is not known how nearly these tests approximated the hypothesized ultraclean surface conditions of the lunar soil material. Thus, although this work represents a valid simulation of both lunar environment and materials, the true surface conditions of the lunar materials may not have been achieved with the test material. The results of this testing could be seriously misinterpreted if this consideration were overlooked. Even though an exact duplication of the lunar soil may not have been achieved, great care was taken to approximate the hypothesized conditions closely.

The particulate sample used was prepared by the Spokane Mining Research Center (5). A large sample of tholeiitic basalt from the Columbia River Basin in central Oregon was first fed into a standard gyratory crusher and then a cone-type gyrator roll crusher (2). The crusher product was passed over 1/8-in (3.2-mm) screen, and the undersize was fed into a 20,000-rpm impact mill. The result was a sample with a size distribution that compared closely with the Apollo 11 samples (fig. 1).

PREPARATION OF SAMPLE FOR UHV

To prepare the particulate sample for the UHV tests, a 170-gram portion of the sample was first baked in a low-vacuum oven (10^{-2} torr) at 135° C for

[4] Underlined numbers in parentheses refer to items in the list of references at the end of this report.

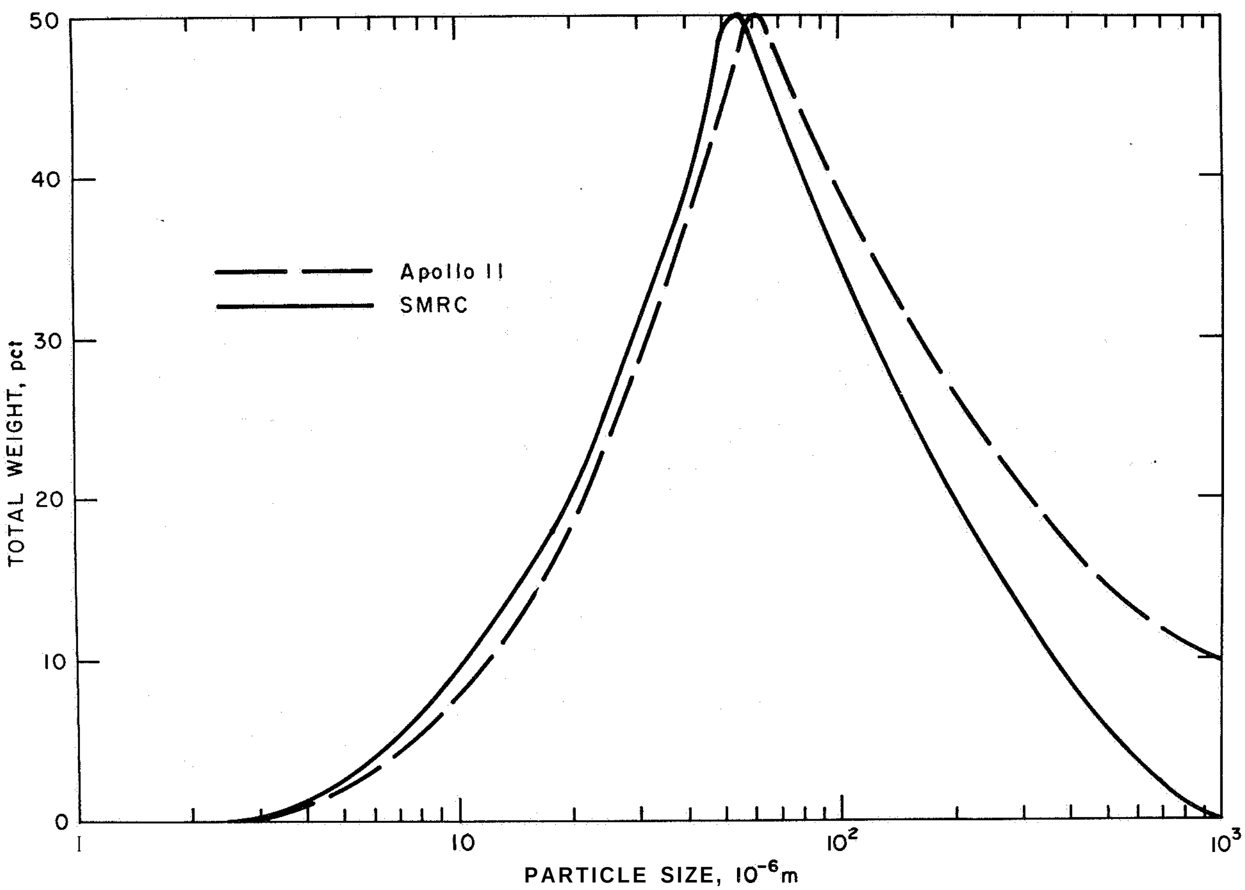


FIGURE 1. - Size distribution curves of simulated lunar soil and Apollo 11 return samples.

1 month. When the sample was in the UHV chamber with pumpdown underway, the sample was stirred intermittently to maximize outgassing of the material before final testing began.

UHV SYSTEM

Experimental equipment used in the torsional shear studies included a UHV system capable of simulating the lunar vacuum (10^{-9} to 10^{-11} torr region), auxiliary measuring devices capable of accurately determining pressure and temperature in the UHV system while experiments were underway, and the experimental apparatus for use in the system to produce shear stresses and sense the resultant torque in a particulate bed of simulated lunar material.

The ion-pumped UHV system had sorption starting pumps and a titanium sublimator to handle the 254-liter volume with a nominal pumping speed of 400 l/sec at standard temperature and pressure. The system could reach a pressure better than 5×10^{-12} torr when baked, clean, and empty. Pressure gaging, in addition to the pump current, included a nude Bayard-Alpert gage and a quadrupole residual gas analyzer (RGA) with a bakeable head. The RGA had a sensitivity of 1×10^{-15} amp/torr for nitrogen, with a mass range from 1 to 500 amu, providing a rapid qualitative method of determining the gas species remaining in the chamber and their relative amounts. The system was equipped with five strap heaters to facilitate bakeout. This bakeout helped the system to degas resulting in a faster pumpdown and a lower ultimate pressure.

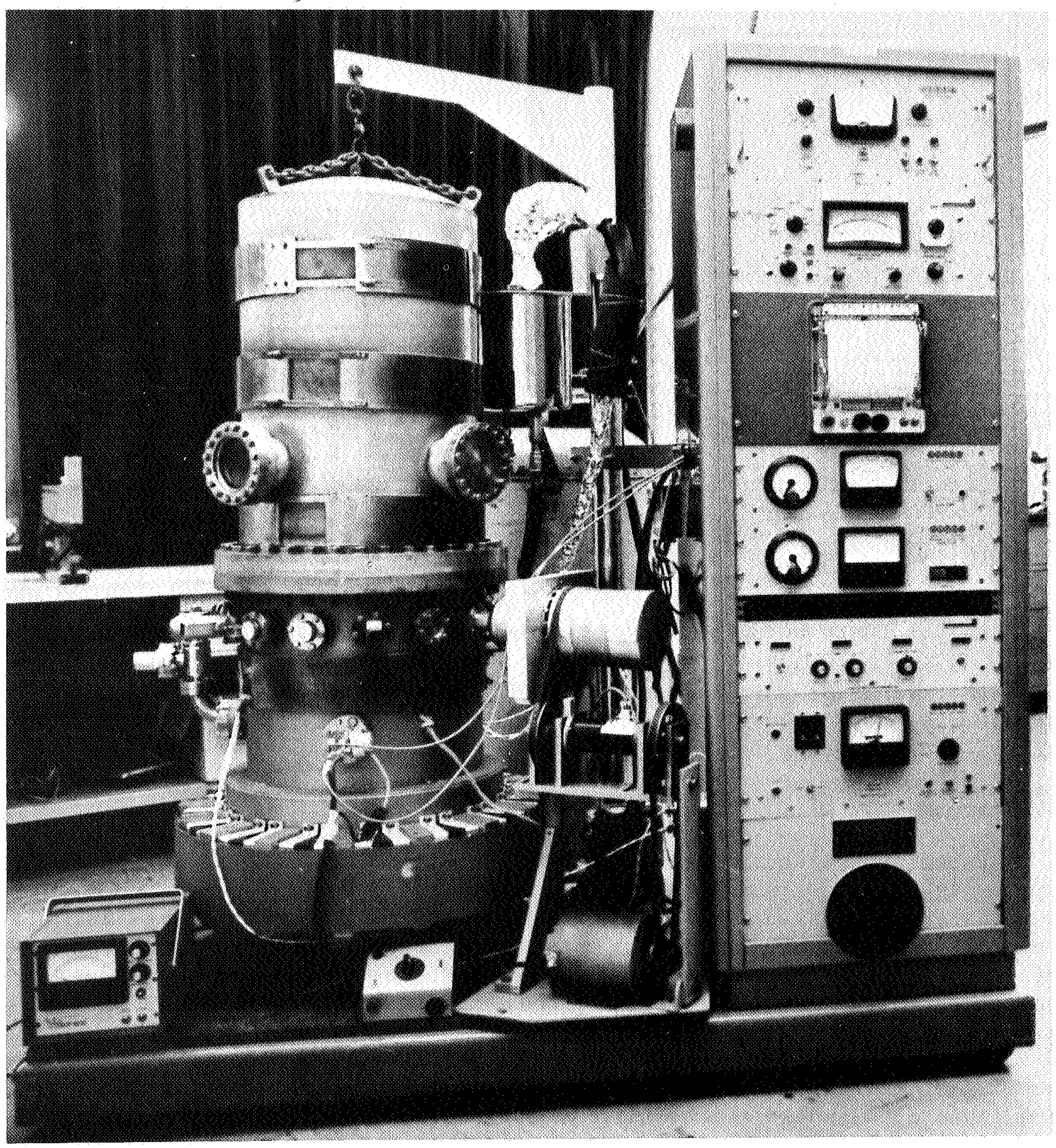


FIGURE 2. - Closed UHV system with console.

Figure 2 shows the UHV system in the laboratory. Working space in the chamber was approximately 24 in (0.61 m) in height by 18 in (0.46 m) in diameter. Twelve 1-1/2-in (0.038-m) ports were located on the circumference of the pump well for instrumentation or motion feedthroughs, and three 6-in (0.15-m) ports were located on the chamber wall to accomodate the viewing windows and the RGA head. The entire vacuum system used copper gaskets, and all rotary motion was either by magnetic coupling or by bellows-sealed eccentric shafts. The driving mechanism for rotating the vane shear head was external to the system but coupled with the internal mechanism through a large magnetically coupled feedthrough. One bellows-sealed linear motion feedthrough was used for holding and positioning the powder bed stirring device, and one bellows-sealed eccentric shaft feedthrough was used to raise and lower the shear head. The system was also equipped with two eight-pin ceramic feedthroughs for electrical connections.

UHV TECHNIQUES

Because of the difficulties associated with attaining a UHV sufficient for a valid lunar environment simulation (10^{-9} to 10^{-11} torr), extreme care in procedures and handling of parts was absolutely mandatory. All hydrocarbons were excluded, and the maximum exclusion of water vapor was essential. Proper system handling therefore began with the general laboratory conditions. This work was conducted in an area where no smoking was allowed and no oil-sealed pumps were used. An attempt was made to keep the relative humidity at less than 35 pct (6.8 gm/m^3) by temperature control at 21" C ±1° C with constant dehumidifying.

When the chamber was backfilled with dry nitrogen and opened for sample insertion, all work was performed with the hands carefully covered to exclude fingerprints. The main copper gasket was replaced, and all electronic circuits and strain gage bridges were checked for correct operation. Sample insertion was performed directly from the vacuum oven where the sample had been preconditioned. The chamber was closed, and the main flange was bolted together. This procedure required that 36 bolts be tightened in opposing pairs by going around twice at 35 ft-lb (47 N-m), twice at 55 ft-lb (75 N-m), and twice at 70 ft-lb (95 N-m). After this initial closure, the system was rough pumped by an oilless carbon-sealed pump, which evacuated the chamber to about 100 torr. The bakeout heaters were on for the last 3 hr of the 4-hr initial roughing cycle. During the final hour of initial roughing, the molecular sieve pumps were chilled by immersion in liquid nitrogen in preparation for the last step of roughing before the system ion pump was started. When the bakeout was shut off and the carbon vane pump was valved off, the first of three sieve pumps was opened to the chamber. Sieve pumping was continued until the pressure reached less than 5 x 10^{-3} torr. This pressure was then low enough for the ion pump to be turned *OR.* Assuming the system had no major leak, the pressure would be less than 10^{-6} torr within 90 sec.

At this point, the quadruple **mass** spectrometer was started, and a thorough leak chasing was performed. This was done by using the **mass** spectrometer tuned to 4 amu so that helium could be used as a tracer gas. When the operator was satisfied that the system was leak free, the bakeout procedure was started. This bakeout period extended as long as necessary for the chamber pressure to rise to a maximum pressure and start going down again. For the testing for this report, the bakeout was shut off after this turn-around point.

After the heaters had been shut off, the cryoshroud was filled, and the titanium sublimator pump (TSP) was used during the cooling period. For the chamber size used in this work, the system required about 18 hr to cool to room temperature. At this equilibrium point, the normal testing procedure started. The elapsed time from opening the chamber to initiation of testing for the sample material and volume used was approximately 2 weeks with most of this time being spent on bakeout and leak chasing.

SHEAR TESTER

The torsional vane shear apparatus was designed for remote operation and UHV compatibility. It made shear strength measurements of simulated lunar soil material possible in a simulated lunar vacuum of 10^{-9} to 10^{-11} torr while still maintaining the same basic concept and elements of a standard torsional vane shear tester. The apparatus, shown in the open chamber in figure 3, has only three major parts: The supporting frame (which was adapted for use from UHV drilling research), the vane shear head with built-in torque sensing, and the sample container with a built-in normal load cell.

The UHV torsional shear tester was patterned after the one developed by Walker for shear testing fine coal (7). The Walker shear tester is significantly different from the more commonly used direct shear tester, but it did allow easier adaptation to the already existing UHV drill frame with only modifications in material and a few minor design changes. The drill frame, made of 316 stainless steel, rested on the bottom of the UHV chamber and was rigidly fastened in place at the main flange by four adjustable tapered shims.

Power for the vane shear head was supplied by a 1/20-hp (37 watts) 12 ft-lb (17 N-m) continuous-duty 2-rpm gear motor coupled to a 280:1 gear reduction box; this assembly was mounted outside the test chamber. The gear box output was coupled by a V-belt to a magnetic feedthrough capable of transmitting 6 ft-lb (8 N-m) of torque. The inside shaft of the magnetic feedthrough was connected through a pair of universal joints to a set of bevel gears. The bevel gears allowed a 90° change in direction so that the horizontal input shaft would drive the vertical spline shaft. The spline shaft and a mating ball bearing spline nut allow the carriage holding the shear head to move vertically. Rotary motion is transferred to the shear head from the spline shaft by a pinion gear on the spline nut mated with a spur gear on the shear head shaft. A schematic diagram of this total power train is shown in figure 4. Although design speed (and thereby the shear strain rate) of the shear head was calculated to be 1/1,800-rpm, the final speed after calibration was found to be 1/2,000-rpm, or approximately 11 pct slower than calculated.

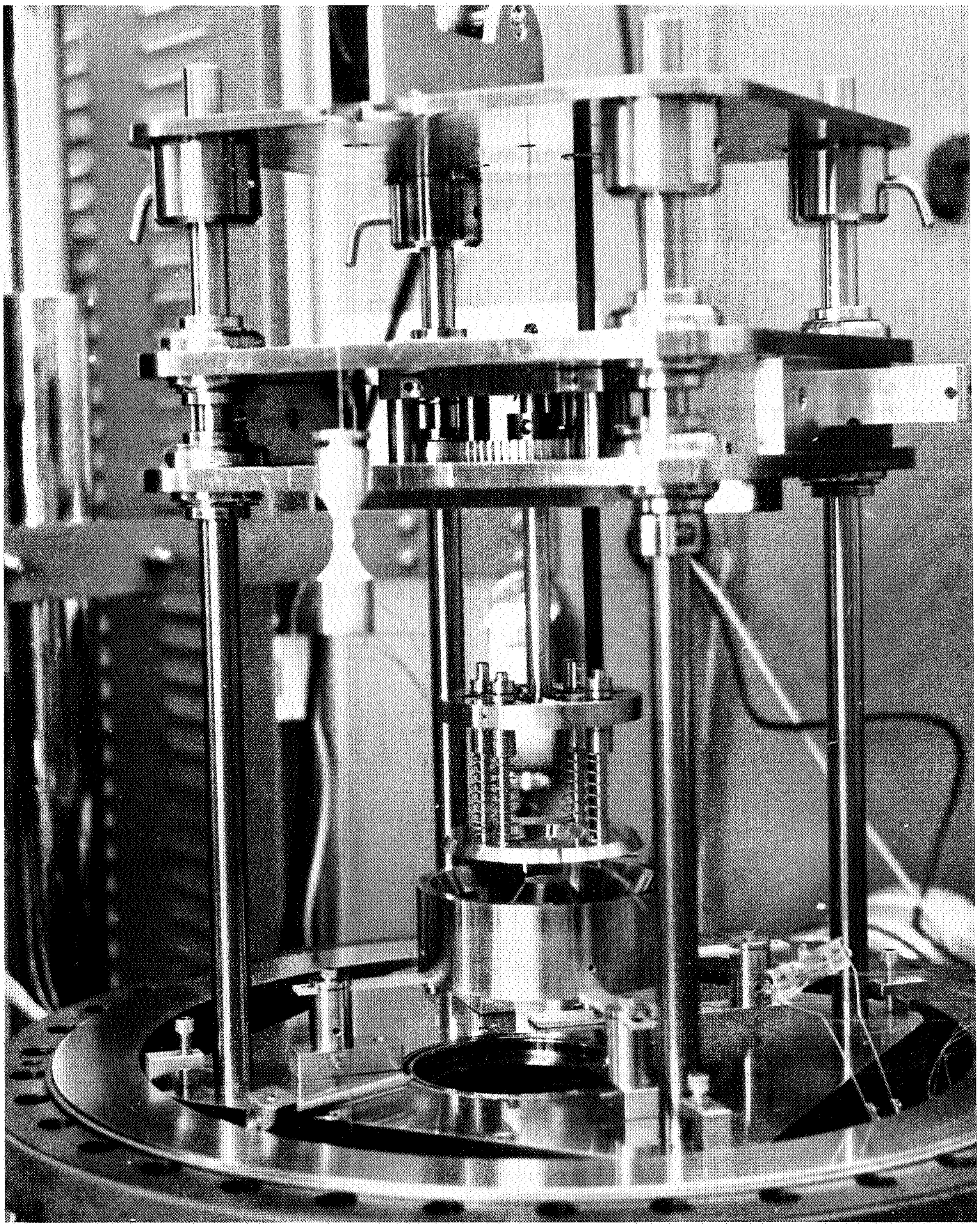


FIGURE 3 - Shear test apparatus in vacuum chamber

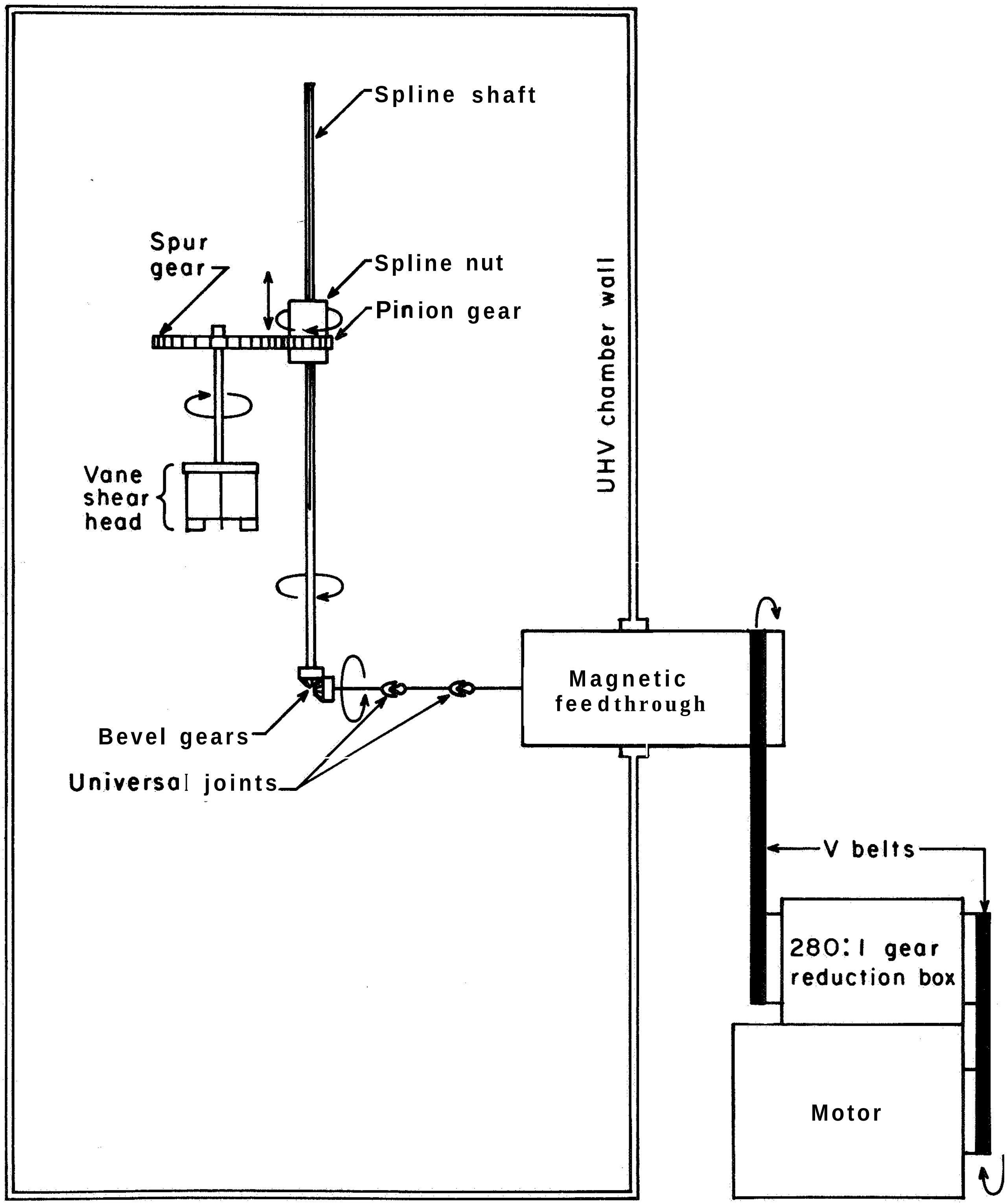


FIGURE 4. - Power train.

The carriage with the vane shear head was moved vertically by a cable running from the top of the carriage over three pulleys and down to a ball nut and screw. The ball nut and screw were used so that unlimited rotary motion could be translated into a large linear motion with a mechanical advantage of 100. Rotary motion was supplied manually by a bellows-sealed rotary feed-through connected to the ball screw on the vacuum side through a pair of universal joints to allow for a small offset. The carriage was thus able to move vertically on the four guide shafts. Linear ball bushings mounted in both the top and bottom plate of the carriage provided easy movement with good alinement.

The top section of the shear head assembly (fig. 5) had four flat spokes that were strain gaged to sense torque on the shear head. The shear head itself had four linear ball bushings mounted in it to allow vertical movement on the supporting rods. Springs with a rating of 2,000 gm/cm were mounted on the supporting posts of the shear head between the head and torque sensor. These springs prevented contact between the two parts and were designed to help maintain a constant normal load during the shear tests (fig. *6).*

The annular sample chamber was supported by four cantilever beams, gaged both top and bottom with an eight-active-gage bridge configuration designed to average the normal force applied to the sample. The bridges were calibrated by deadweight loading.

The stirring device, although not used during the actual shear test, allowed the sample to be thoroughly mixed and leveled before each test and thus permitted making an infinite number of tests with one pumpdown. All moving parts in the system were coated with MoS_2 to prolong working life without affecting the integrity of the UHV.

PERFORMANCE OF TESTS

The first step in each test cycle was stirring to mix and level the soil. This was accomplished by positioning the vane shear head to facilitate mating of the head and stirring device. After joining the stirring device to the vane shear head, the combination was rotated 90° to remove the stirring device from its storage holder. The storage holder was then retracted so that the combination could be lowered. This sequence of events is shown in figure 7A-F. After the stirrer was rotated through two revolutions at a maximum depth of *0.84* in (0.021 m), the head and stirrer were slowly raised while rotation was continued. Finally, the combination was rotated several revolutions with the stirring device just touching the surface of the soil to level the soil completely. The head was then decoupled from the stirring device by returning the stirrer to its holder and moving it back out of the way. At this time all strain gage bridge imput voltages were checked. The bridge output and the X-Y recorders were checked for electrical and/or mechanical zeroes.

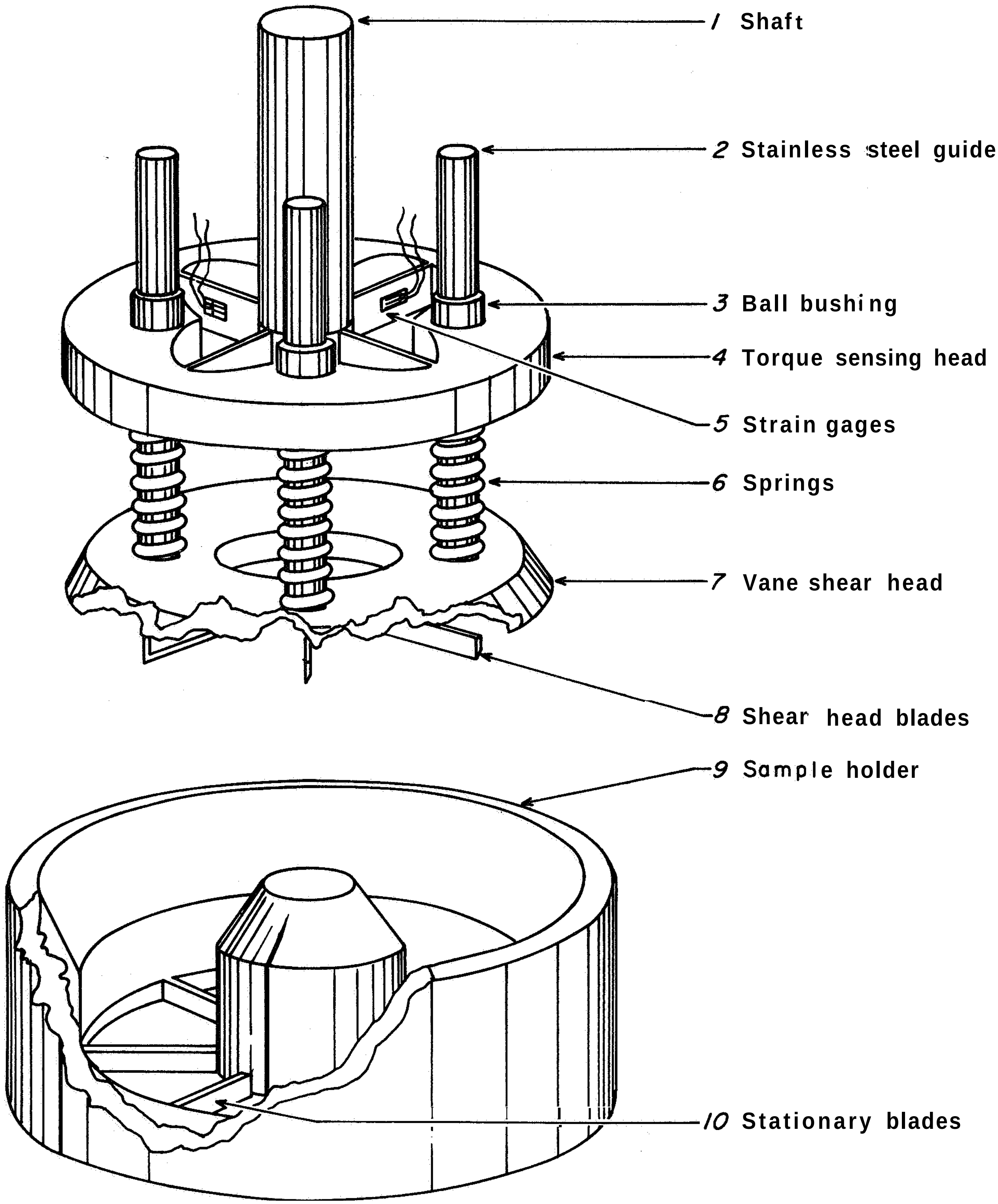


FIGURE 5. - Shear tester,

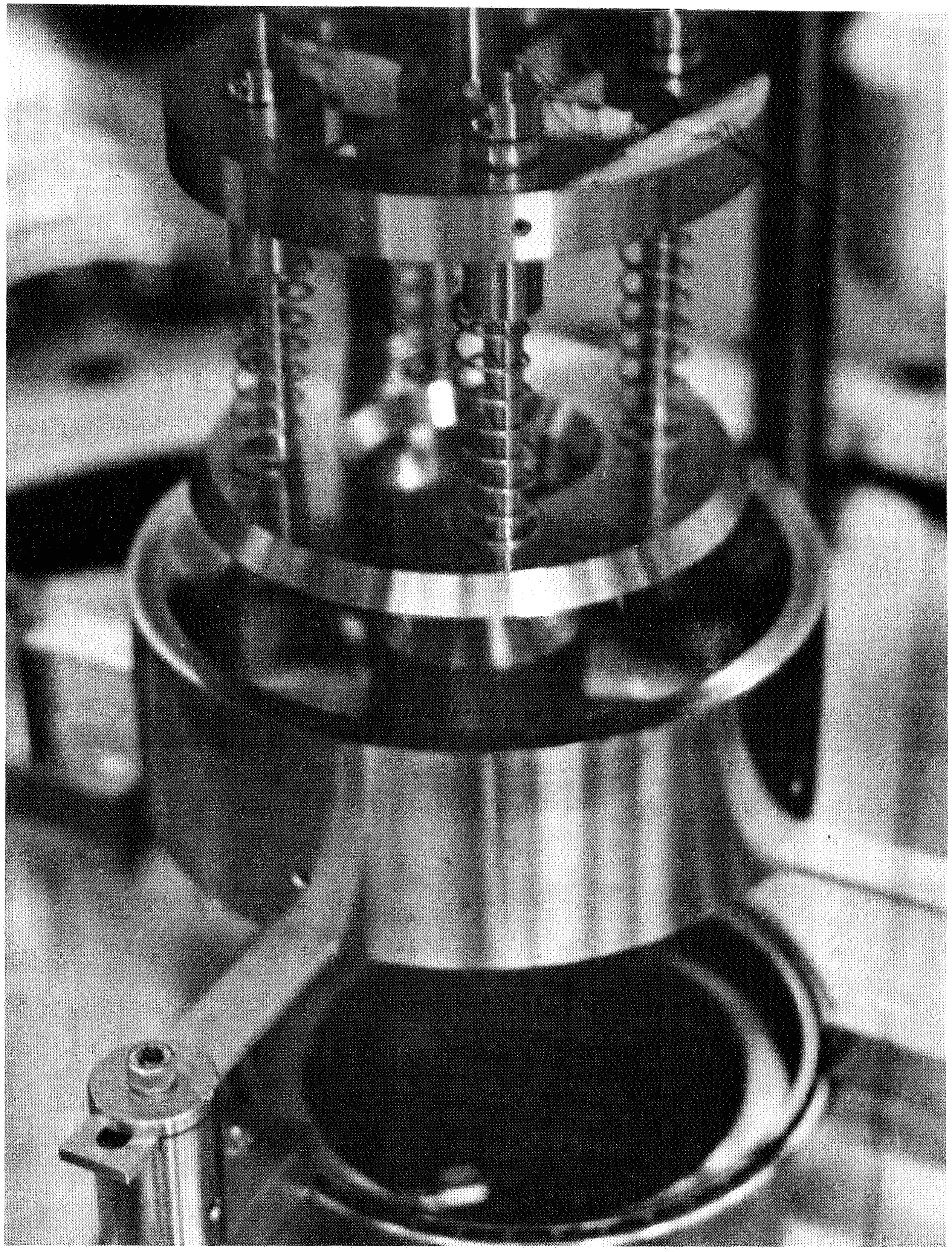
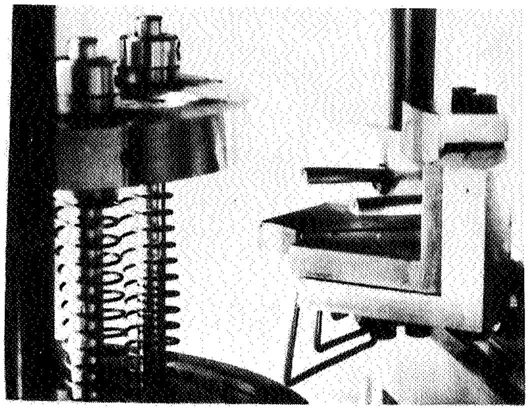
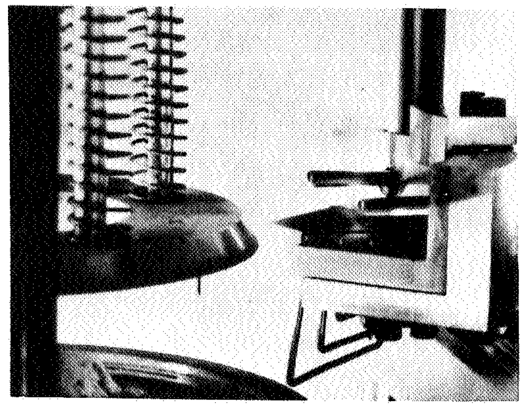


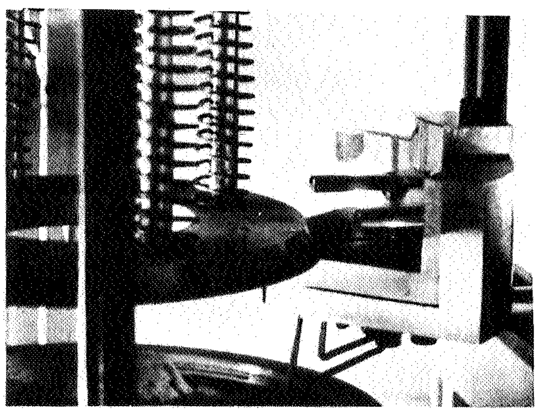
FIGURE 6. - Closeup of shear tester.



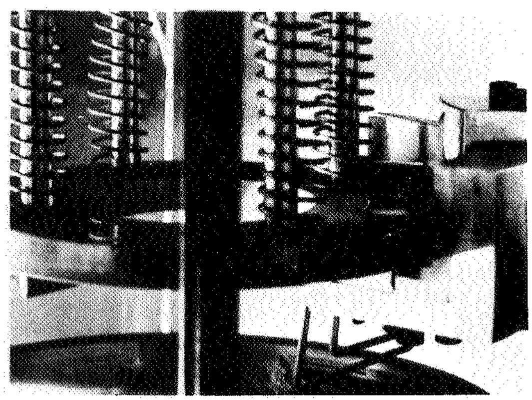
A



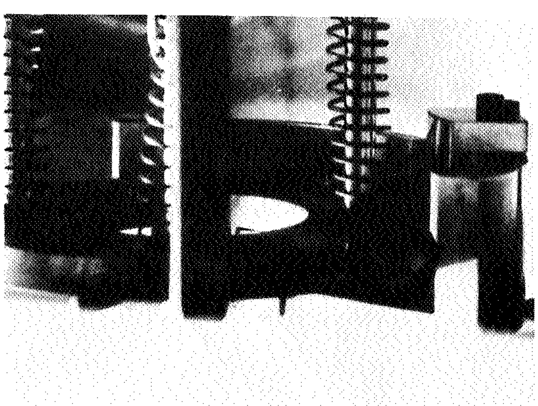
B



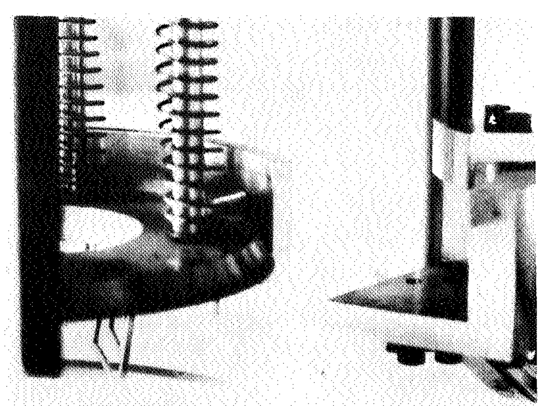
C



D



E



F

FIGURE 7. - Mating of stirring device with shear head.

After recording the gas pressure in the chamber, the vane shear head was lowered to the consolidating load level for 1 hr and then readjusted to the normal load shearing level dictated by the test. With the recorders on, the electric driving motor for the vane shear head was started. Normal load was maintained at a constant level throughout the test. The test continued until the tangential load reached its final plateau, which usually took about 1-1/2 hr (16° of rotation) depending on the shearing load, that is, the higher the load the longer it took. After a test was completed, the vane shear head was raised, and the bridges and recorders were rechecked for zero shifts. Any discrepancy in zeroes caused the test to be rerun. The pressure was recorded again, and the apparatus was ready for the next test.

To determine the effect of UHV on the shear strength of SLS, duplicate tests were run in both UHV and controlled laboratory atmospheric conditions. In a standard test series, the sample was first sheared at a normal load equal to the consolidating load; for the remaining cycles in the series, the SLS was stirred and leveled again then sheared under a normal load that was decreased 1 kg per cycle until a normal load of 1 kg was reached. Thus, for laboratory atmospheric and UHV conditions, the 6-kg series contained six test cycles and, the 1-kg series contained one test cycle.

DATA ANALYSIS

The results of the tests are shown in table 1. The data were analyzed by the use of the least-squares method. The resulting straight-line equations are shown in table 2. The data from the 3-, 4-, 5-, and 6-kg series were also graphed (figs. 8-11). The percentage increase in the shear force is shown in table 1 also.

Further analysis to determine the difference between tests in laboratory atmosphere and UHV was accomplished by applying a linear model and the analysis of variance to the data from the 3-, 4-, 5-, and 6-kg series. The linear model used was as follows:

$$Y(k,i) = \text{normal load } (k) + I(i) \cdot A + \text{error } (k,i),$$

where k is the normal load in kg,

$$I(i) = 0 \quad i = 1$$
$$= 1 \quad i = 2$$

$Y(k,i)$ is an observed test point at k kg of normal load and for tests in a vacuum $i = 2$ or in atmosphere $i = 1$,

and error (k,i) is experimental error.

The focus of attention is on A, which represents the increase (averaged over the range of data) in ultimate shearing force when the tests are performed in a UHV. This analysis is shown in table 3.

TABLE 1 - Test [illegible]

Consolidation load		Normal load		Normal stress		Laboratory atmosphere				Ultrahigh vacuum					Pct increase in shear force
						Shear force		Shear stress		Shear force		Shear stress		Pressure, torr x 10^{-9}	
Kg	Lb	Kg	Lb	N/m²	Psi	Kg	Lb	N/m²	Psi	Kg	Lb	N/m²	Psi		
6	13.2	6	13.2	8,900	1.29	6.2	13.6	9,200	1.33	6.7	14.7	10,100	1.46	6.2	8.1
6	13.2	6	13.2	8,900	1.29	6.2	13.6	9,200	1.33	6.7	14.7	10,100	1.46	6.2	8.1
6	13.2	6	13.2	8,900	1.29	6.2	13.6	9,200	1.33	6.7	14.7	10,100	1.46	6.2	8.1
6	13.2	6	13.2	8,900	1.29	6.2	13.6	9,200	1.33	6.7	14.7	10,100	1.46	6.2	8.1
6	13.2	6	13.2	8,900	1.29	6.2	13.6	9,200	1.33	6.7	14.7	10,100	1.46	6.2	8.1
6	13.2	5	11.0	7,500	1.09	4.9	10.8	7,300	1.06	5.2	11.4	7,700	1.12	5.9	6.1
6	13.2	4	8.8	6,000	.87	3.5	7.7	5,200	.75	3.9	8.6	5,800	.84	4.7	11.4
6	13.2	3	6.6	4,500	.65	2.6	5.7	3,900	.57	2.8	6.2	4,200	.61	5.2	7.7
6	13.2	3	6.6	4,500	.65	2.6	5.7	3,900	.57	2.8	6.2	4,200	.61	5.2	7.7
6	13.2	3	6.6	4,500	.65	2.6	5.7	3,900	.57	2.8	6.2	4,200	.61	5.2	7.7
6	13.2	3	6.6	4,500	.65	2.6	5.7	3,900	.57	2.8	6.2	4,200	.61	5.2	7.7
6	13.2	2	4.4	3,000	.43	1.3	2.9	1,900	.28	1.5	3.3	2,200	.32	4.2	15.4
6	13.2	1	2.2	1,500	.22	.6	1.3	900	.13	.7	1.5	1,000	.15	4.4	16.7
5	11.0	5	11.0	7,500	1.09	5.0	11.0	7,500	1.09	5.5	12.1	8,200	1.19	6.9	10.0
5	11.0	4	8.8	6,000	.87	3.9	8.6	5,800	.84	4.6	10.1	6,800	.97	6.4	17.9
5	11.0	3	6.6	4,500	.65	2.8	6.2	4,200	.61	3.2	7.0	4,800	.70	6.3	14.3
5	11.0	2	4.4	3,000	.43	1.7	3.7	2,500	.36	2.2	4.8	3,300	.48	6.2	29.4
5	11.0	1	2.2	1,500	.22	.7	1.5	1,000	.15	1.0	2.2	1,500	.22	6.6	42.9
4	8.8	4	8.8	6,000	.87	4.0	8.8	6,000	.87	4.7	10.3	7,000	1.02	7.6	17.5
4	8.8	3	6.6	4,500	.65	2.8	6.2	4,200	.61	3.3	7.3	4,000	.71	7.4	17.9
4	8.8	2	4.4	3,000	.43	1.7	3.7	2,500	.36	2.0	4.4	3,000	.44	7.2	17.6
4	8.8	1	2.2	1,500	.22	.7	1.5	1,000	.15	.8	1.8	1,200	.17	7.1	14.3
3	6.6	3	6.6	4,500	.65	3.2	7.0	4,800	.70	3.7	8.1	5,500	.80	2.6	15.6
3	6.6	2	4.4	3,000	.43	2.3	5.1	3,400	.49	2.7	5.9	4,000	.58	2.1	17.4
3	6.6	1	2.2	1,500	.22	1.5	3.3	2,200	.32	1.7	3.7	2,500	.36	2.2	13.3
2	4.4	2	4.4	3,000	.43	1.9	4.2	2,800	.41	2.8	6.2	4,200	.61	2.4	47.4
2	4.4	1	2.2	1,500	.22	1.0	2.2	1,500	.22	1.2	2.6	1,800	.26	2.5	20.0
1	2.2	1	2.2	1,500	.22	.9	2.0	1,300	.19	1.2	2.6	1,800	.26	2.2	33.3

Consolidating	Equation	Coefficient of
6	$y = -0.75 + 1.21x$	0.997
5	$y = -0.12 + 1.14x$	.998
4	$y = -0.55 + 1.30x$	.999
3	$y = 0.70 + 1.00x$	1.000
	TESTS IN ATMOSPHERE	
6	$y = -0.79 + 1.13x$	0.996
5	$y = -0.42 + 1.08x$	1.000
4	$y = -0.45 + 1.10x$	.999
3	$y = 0.63 + .85x$	.999

x = Normal load in kilograms,

TABLE 3. - Analysis of variance

Normal load......	6	461.55	-	-	-
Delta............	1	.54	0.54	54 (4.5)	0.31
Error............	15	.15	.010		-
Total	22	462.24	-	-	-
Normal load......	5	118.30	-	-	-
Delta............	1	.58	0.58	52 (5.0)	0.48
Error............	4	.044	.011	-	
Total	10	118.92	-	-	-
Normal load......	4	64.42	-	-	-
Delta............	1	.32	0.32	10 (10)	0.40
Error............	3	.10	.033	-	-
Total..	8	. 64.84	-	-	-
Normal load......	3	41.43	-	-	-
Delta............	1	.20	0.20	17 (18.5)	0.36
Error............	2	.023	.012	-	-
Total	6	41.65	-	-	-

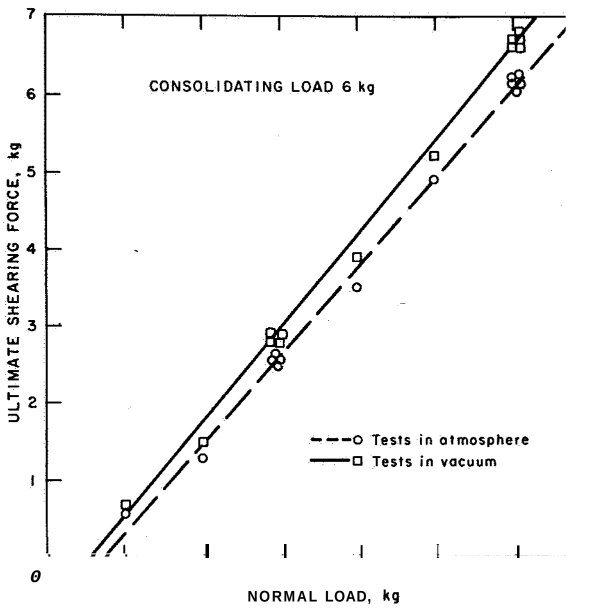


FIGURE 8. - Shearing force graph for 6-kg normal load,

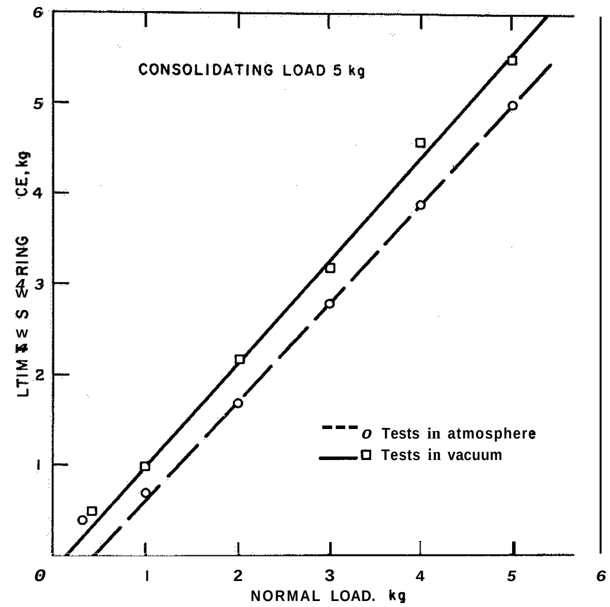


FIGURE 9. - Shearing force graph for 5-kg normal load.

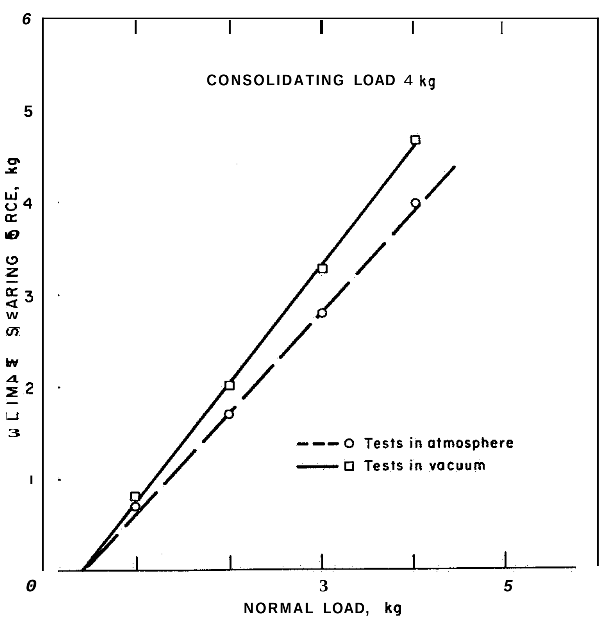


FIGURE 10. - Shearing force graph for 4-kg normal load.

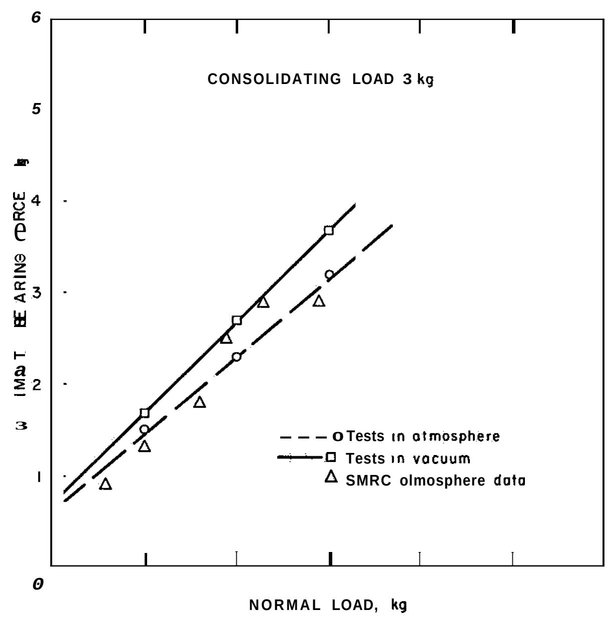


FIGURE 11. - Shearing force graph for 3-kg normal load.

Delta is clearly significant for the 5- and 6-kg series, marginally significant for the 4-kg series, and fails to be significant for the 3-kg series. The loss of significance in the 3- and 4-kg series is probably due to the limited amount of data available. Data from Spokane Mining Research

Center are shown on the 3-kg series graph; however, there were not enough data to look at statistically.

CONCLUSIONS AND RECOMMENDATIONS

The results show that the shear strength of SLS is definitely affected by the environment. Shear strength of the SLS tested in UHV increased over all tests conducted in a controlled laboratory environment. These test results indicate that materials handling in the lunar environment will require a substantial increase in energy.

This research has shown conclusively that it is possible to design operational equipment for moderate loads operating in UHV conditions. This work is significant not only for the testing potential of the apparatus but because it has shown that operating mechanisms may be designed that will not degrade mirrors or invalidate other nearby instrument results owing to outgassing during operation in the hard vacuum of space,

It is recommended that further work on this problem be expanded to include the full temperature range of the lunar surface. Future studies should also include the use of some uncontaminated lunar soil so that a direct comparison might be obtained. Fundamental studies should also be made to determine the processes that cause the increased shear strength.

REFERENCES

1. Atchison, T. C., and C. W. Schultz. Bureau of Mines Research on Lunar Resource Utilization. Proc. 6th Ann. Meeting of Working Group on Extraterrestrial Resources, Brooks Air Force Base, San Antonio, Tex., Feb. 19-21, 1968, NASA SP-177, pp. 65-74.

2. Fogelson, D. E. Simulated Lunar Rocks. Proc. 6th Ann. Meeting of Working Group on Extraterrestrial Resources, Brooks Air Force Base, San Antonio, Tex., Feb. 19-21, 1968, NASA SP-177, pp. 75-95.

3. Jenkie, A. W. Gravity Flow of Bulk Solids. Bull. 108, Univ. of Utah, Salt Lake City, Utah, v. 52, No. 29, October 1961, 309 pp.

4. Karafiath, L. L., and G. Mohr. The Effect of Ultrahigh Vacuum on the Friction Between Various Solids and Granular Soils. Geo-Astrophysics Sec., Grumman Research Dept. Rept. RE 376, March 1970, pp. 22-194.

5. Nicholson, D. E. Gravity Flow of Powder in a Lunar Environment (in Two Parts). Property Determination of Simulated Lunar Soil. BuMines RI 7543, 1971, 34 pp.

6. Roepke, W. W. Friction Tests in Simulated Lunar Vacuum. Proc. 7th Ann. Meeting of Working Group on Extraterrestrial Resources, NASA SP-229, June 1969, pp. 107-112.

7. Walker, D. M. A Basis for Buncier Design. Powder Technol., v. 1, No. 4, December 1967, pp. 228-236.